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Resonant Full-Bridge Synchronous Rectifier Utilizing 15 V GaN Transistors for Wireless Power Transfer Applications Following AirFuel Standard Operating at 6.78 MHz

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Abstract—Connectivity in smart devices is increasingly realized by wireless connections. The remaining reason for using connectors at all is for charging the internal battery, for which wireless power transfer is an alternative. Two industry standards, AirFuel and Qi, exist to support compatibility between devices. This work is focusing on the AirFuel standard, as it is operating at a higher frequency (6.78 MHz), than the Qi standard, and therefore allows smaller passive components, including the coupling coils. Whereas gallium-nitride (GaN) devices are being widely used on the transmitter (Tx) side, this work uses low voltage GaN transistors on the receiver (Rx) side to allow synchronous rectification and soft switching, thereby achieving high efficiency. After analyzing adequate Class-DE rectifier topologies, a Class-DE full-bridge 5 W rectifier using 15 V GaN transistors are designed and implemented. The experimental results show an efficiency above 80 % over a wide operating range and a peak efficiency of 89 %, at an arbitrary alignment of Tx and Rx coils with 3 cm distance between them.

Index Terms—Wireless power transfer, AirFuel, synchronous rectification, resonant circuit, soft-switching, GaN devices.

I. INTRODUCTION

In recent years, the attention to wireless charging technologies for consumer applications, as shown in Fig. 1, has grown dramatically. Avoiding the connectors in smartphones and tablets allow for a further increase in their robustness (e.g. water proof cases) and gives more space for energy storage in the battery to increase the battery life. Therefore, two standards were created; Qi [1] and AirFuel [2]. Research activities, addressing the lower frequency (87 - 205 kHz) Qi standard [3]–[7] and the higher frequency (6.78 MHz) AirFuel standard [8]–[18], grew as well. Some work [19], [20] are targeting both standards and other work [21], [22] reported operation outside those standards. Higher frequencies promise size reduction of passive components. In terms of wireless charging applications, this results in smaller transmitter (Tx) and receiver (Rx) coils. Therefore this work focuses on the AirFuel standard. Gallium nitride (GaN) devices are used in [12], [15], [18] to reduce switching losses on the Tx side. Synchronous rectifiers, typically used in high power applications [23], [24], address the conduction losses on the Rx

side in [3], [7], [13]. This work combines these two advantages on the Rx side with a synchronous rectifier based on GaN devices, fulfills the AirFuel standard [2] and addresses the specification in table I. This paper presents the work of [25].

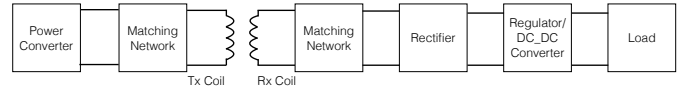


Fig. 1. Block diagram of the elements in a wireless power transfer (WPT) system

TABLE I
DESIGN SPECIFICATIONS

Output power P_{out}	5 W
Output voltage V_{out}	5 V
Operating frequency f_{sw} [2]	6.78 MHz

II. TOPOLOGY SELECTION

Synchronous rectification for WPT is being researched, as it is a potential way to overcome the losses associated with diodes, which are currently used in WPT systems. Other work such as [3], [4], [7], [13], [14], [26]–[28] look into ways to implement and optimize control schemes for synchronous rectifiers.

This work uses a comparator to sense the voltage across the synchronous rectifier, as shown in Fig. 2 based on [25]. To overcome propagation delay of the gate driver, a delay is implemented between the comparator and the gate driver. This helps correct the delay of the last period in the next switching period, which is tuned to achieve soft switching.

Resonant topologies [10], [14], [16], [17], [29] are very promising for wireless charging applications, as they allow precise impedance matching to the Tx and Rx coils and simultaneously provide high energy efficiency due to their ability to soft-switch the power devices.

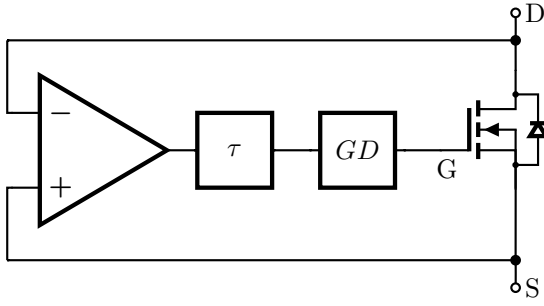


Fig. 2. Block diagram of the synchronous rectification circuit. τ is delay compensation and GD is the gate driver.

Whereas [10], [14], [16], [17], [29] use the Class-E topology to avoid high-side switches and therefore come with a high voltage stress across the power semiconductor, [30], [31] document the Class-DE topology and its corresponding high-side gate driver [32], [33] as alternative. Within the current-driven Class-DE rectifier family, Fig. 3 shows three members.

For the implementation in this work, each of the diodes is replaced with a comparator-transistor combination shown in Fig. 2.

Three topologies were investigated: the Class-DE half-bridge rectifier described in Fig. 3a [34], a Class-DE full-bridge rectifier based on the half-bridge in Fig. 3b and the half-wave Class-DE low dv/dt rectifier described in Fig. 3c [35]. These three topologies were simulated in LTspice with synchronous rectification instead of diodes. To find the transistor with the best performance for the specifications, multiple transistors were analyzed using figures of merit (FOM).

A. Transistor FOM Analysis

With the help of figures of merit, see (1) - (3), several potential power devices are investigated based on their datasheet parameters [36]–[41]. The result of the investigation is shown in table II.

$$FOM_1 = Q_{ISS} \cdot R_{DSon} \quad (1)$$

$$FOM_2 = Q_{GD} \cdot R_{DSon} \quad (2)$$

$$FOM_3 = Q_{OSS} \cdot R_{DSon} \quad (3)$$

The FOM_2 says something about the frequency range the device can operate in, where Q_{GD} is the gate-drain charge, but the focus is on the input characteristics FOM_1 and the output characteristics FOM_3 . Q_{ISS} and Q_{OSS} are the input charge and output charge of a transistor respectively. Q_{ISS} is found from the datasheet Q_G vs. V_{GS} plots for the given drain-source. Some of the datasheets do not show the plot for 5 V drain-source voltage, in which case 6 V or 4.5 V is used. Q_{OSS} is approximated by integrating output capacitance C_{OSS} in the full drain-source voltage range. This is important as the capacitances vary with voltage. R_{DSon} is the resistance from drain to source when the transistor is in the ON-state.

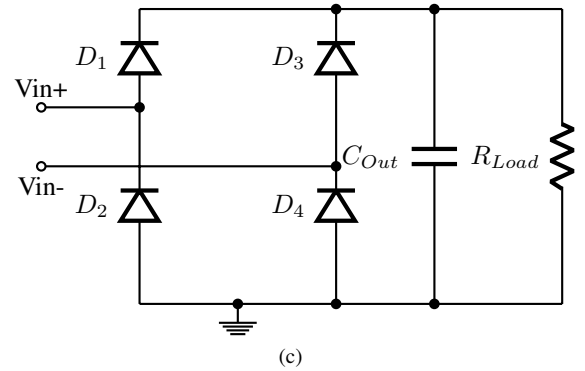
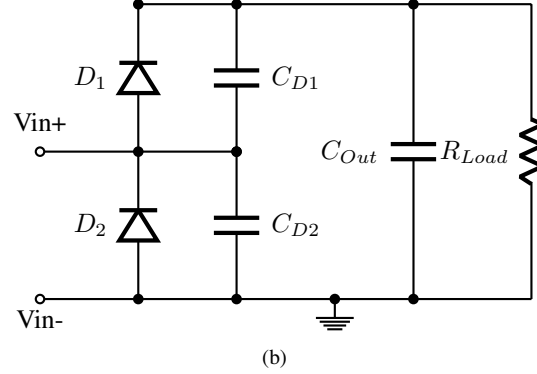
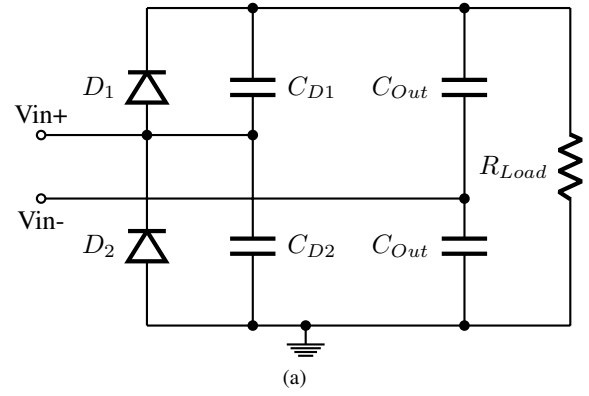


Fig. 3. Current driven soft-switching rectifier circuits. (a) is the Class-DE half-bridge rectifier, (b) the Class-DE full-bridge rectifier and (c) the half-wave Class-DE low dv/dt rectifier.

This method of evaluating transistors based on their FOM has also been done in works like [42].

Comparing the GaN EPC2040 [36] device in table II with the silicon (Si) based devices [37]–[39], [41], the GaN device is superior by a factor of 6 and 3 with respect to FOM_1 and FOM_3 and therefore chosen. A visualization of the transistor FOM can be seen in Fig. 4.

$$I_{out} = \frac{I_m}{2\pi} \rightarrow I_m = 6.28 \text{ A} \quad (4)$$

$$V_{out} = \frac{I_m}{\omega(C_{D1} + C_{D2})} \rightarrow C_{D1} + C_{D2} = \frac{I_m}{V_{out} \cdot \omega} \quad (5)$$

$$\rightarrow C_{D1} = C_{D2} = 14.75 \text{ nF}$$

TABLE II
TRANSISTOR SELECTION BASED ON FOM1 AND FOM3 BASED ON DATA FROM [36]–[41]

Transistors:	Voltage Rating [V]	R_{DSon} [m Ω]	Q_{iss} [pC]	Q_{oss} [pC]	FOM_1 [pVs]	FOM_3 [pVs]
EPC2040 (GaN) [36]	15	28	745	357	20.86	9.996
SiUD412ED (Si) [38]	12	340	500	102	170	34.68
Si4838DY (Si) [39]	12	3	45000	15717	135	47.15
Si2342DS (Si) [40]	8	17	10500	2508	178.5	42.63
DMN1260UFA (Si) [41]	12	366	1050	211	384.3	77.35
Si1050X (Si) [37]	8	86	7900	1277	679.4	109.83

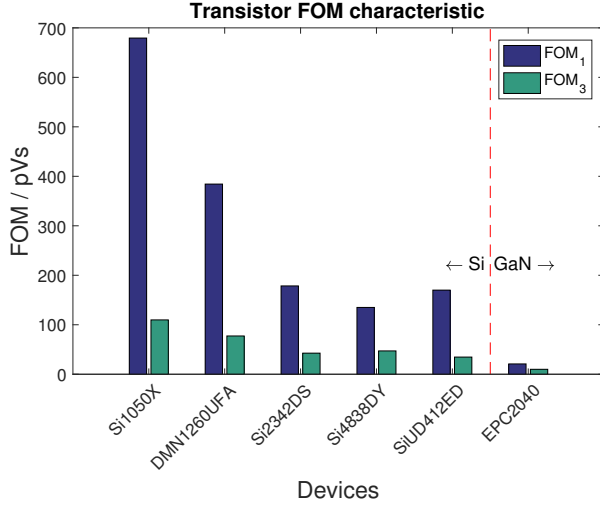


Fig. 4. Visualization of the transistors FOM values

The method presented in [35] with the specifications from this work, results in the need of extra capacitance at the drain-source of each transistor, as the EPC2040 only has 70 pF drain-source capacitance [36]. The equations from [35] are shown in (4) and (5), where I_{out} and I_m are the output current and magnitude of the input current respectively. V_{out} is the output voltage, C_{D1} and C_{D2} are the drain-source capacitances and ω is the angular frequency of the input signal. Any deviation from soft-switching would result in large switching losses due to the added capacitance, which is undesired. With the added capacitance the input current amplitude is 6.28 A, see (4). In the simulation, it is found that having only the drain-source capacitance of the EPC2040 results in an input current amplitude of 3.14 A, for both half-bridges. The input current amplitude of the full-bridge is 1.57 A, when using only the EPC2040 drain-source capacitance.

B. Component Stress Factors

$$SCSF_i = \frac{\sum_j W_j}{W_i} \frac{V_{max,i}^2 I_{RMS,i}^2}{P^2} \quad (6)$$

$$CCSF_i = \frac{\sum_j W_j}{W_i} \frac{V_{max,i}^2 I_{RMS,i}^2}{P^2} \quad (7)$$

Component stress factors (CSF) are used to evaluate the three topologies and to see which best fits with the specifications. As

there are no inductive elements in any of the three topologies, only the semiconductor stress factor (SCSF) and capacitive component stress factor (CCSF) is calculated, see (6) and (7). Here V_{Max} is the maximum voltage the component experiences and the I_{RMS} is the RMS current running in that component. W_j and W_i are weighting factors. In this work, each stress factor is weighted equally. P is the output power of the converter. The voltages and currents V_{Max} and I_{RMS} for each component in each converter are found via the LTspice simulation. The total SCSF and CCSF for each converter are shown in table III.

TABLE III
CALCULATED COMPONENT STRESS FACTORS OF THE THREE TOPOLOGIES WITHOUT WEIGHTING

Topology:	SCSF	CCSF
Class DE Half-Wave low dv/dt Rectifier:	4.93	1.47
Class DE Half-Bridge Rectifier:	4.93	0.74
Class DE Full-Bridge Rectifier:	2.47	0.25

The full-bridge is shown to experiences the fewest stresses on the components. Furthermore, it also has a small amplitude on the output voltage ripple due to the fact that it conducts power in both switching periods. This is also the reason for the lower input current. Based on the CSF analysis the full-bridge topology is chosen.

III. IMPLEMENTATION

Choosing the GaN device EPC2040 [36] for synchronous rectification, a GaN compatible gate driver is required. The gate driver also has to have a supply voltage lower than the output voltage of the receiver, as it would, in a commercial product, be supplied from the output. In this work the drive circuitry is supplied from an external source to ensure performance stability in the tests. A block diagram of the full-bridge rectifier is shown in Fig. 5, with the four EPC2040 GaN devices and two LM5113 gate drivers. The voltage sensor and delay compensation for each high side controls the drive signals for the high side in one branch and the low side for the other branch. The delay compensation has been empirically tuned for these exact components. V_D represents the external source for the control circuit. The gate resistors R_{Gate} limit the current which charges the gate capacitances to protect the GaN devices.

The designed full-bridge rectifier circuit is implemented on a printed circuit board (PCB), as shown in Fig. 6, which is optimized for laboratory measurement purposes. For the final

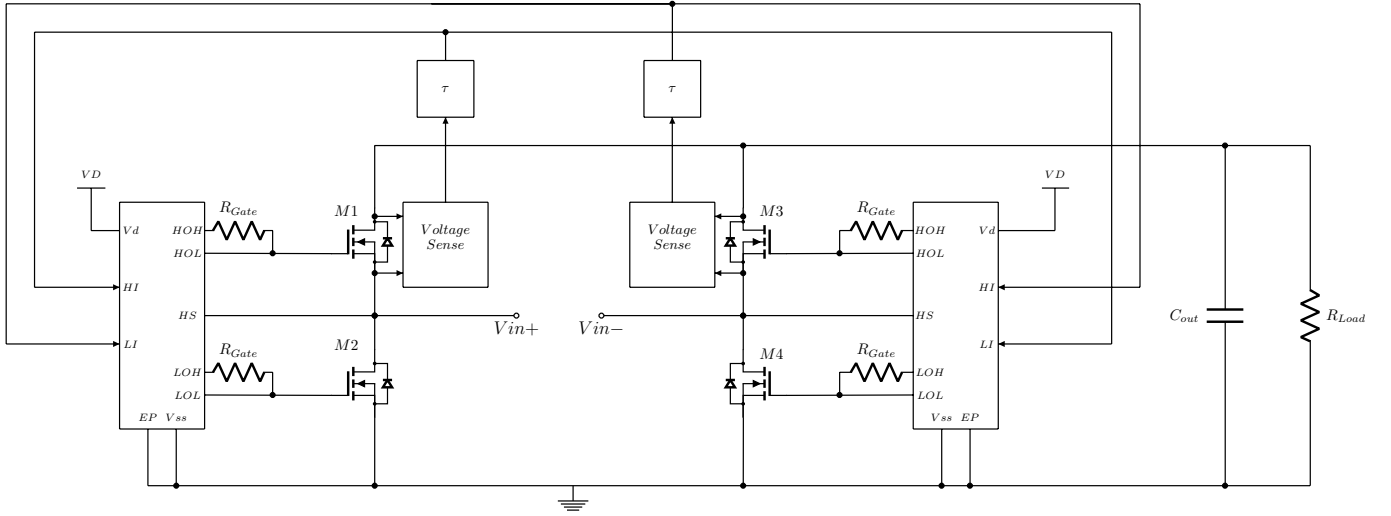


Fig. 5. Block diagram of the proposed Class-DE full-bridge rectifier with synchronous rectification.

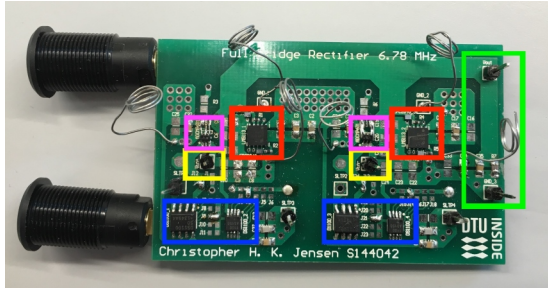


Fig. 6. Prototype PCB. Red: gate driver and GaN devices, blue: feedback, yellow: input, pink: comparator and Green: output.

product design, the circuit can be implemented with higher power density.

A. Impedance Matching

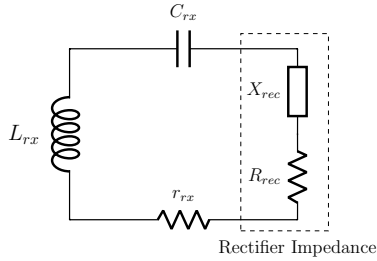


Fig. 7. Equivalent circuit for impedance matching. L_{rx} and r_{rx} are the coil inductance and ac resistance at 6.78 MHz, C_{rx} is the matching compensation capacitor, and X_{rec} and R_{rec} are the rectifiers input reactance and resistance.

$$j\omega L_{rx} + \frac{1}{j\omega C_{rx}} + jX_{rec} = 0 \quad (8)$$

$$C_{rx} = \frac{1}{\omega(\omega L_{rx} + X_{rec})} \quad (9)$$

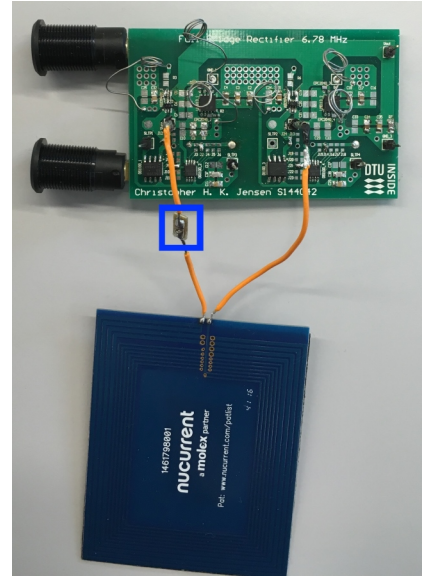


Fig. 8. Prototype PCB with receiver coil connected. Blue: C_{rx}

Impedance matching between the rectifier and the receiver coil is needed to get maximum power transfer at the given operating frequency.

Fig. 7 shows the equivalent impedance circuit of the receiver coil and rectifier. R_{rec} and X_{rec} represent the rectifier impedance. L_{rx} and r_{rx} are the inductance and resistance of the receiver coil at the operating frequency of 6.78 MHz. At resonance, the reactance should be zero. A compensation capacitor C_{rx} is added in series with the coil and rectifier to achieve resonance, see (8) and (9).

Fig. 8 shows the prototype with the receiver coil, where the green PCB on top is the implemented rectifier, the blue PCB (bottom) is the Rx coil and the blue box in the middle marks C_{rx} .

The prototype full-bridge rectifier and receiving coil to-

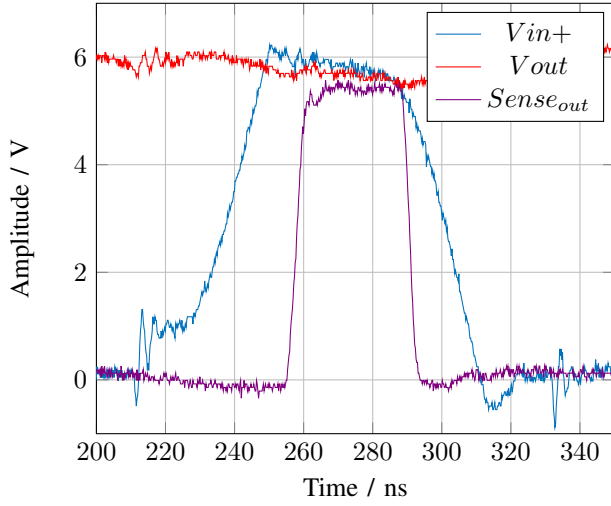


Fig. 9. Measured waveforms. V_{in+} and V_{out} are the inputs of the voltage sense circuit and $Sense_{out}$ is the output of the sense circuit



Fig. 10. Measurement setup for the efficiency measurements. Red: receiver coil, blue: inverter, purple: rectifier, orange: compensation capacitor and the large blue plate is the transmitter coil.

gether with the transmitter coil and power amplifier from the EPC9112 demo kit [43] are combined to form a WPT system.

IV. EXPERIMENTAL RESULTS

The waveforms of the prototype are verified with a LeCroy WavSurfer 104MXs-B, 1 GHz, 10 GS/s oscilloscope and for better visualization plotted in Fig. 9 with the help of MATLAB. The waveform drawings in Fig. 9 show the soft-switching of the power devices.

Fig. 10 shows the measurement setup for the input power sweep. The red box indicates the placement of the receiving coil on top of the transmitter coil (large blue plate). The blue square in the bottom of the picture shows the power amplifier which drives the transmitter coil. On the right side the rectifier (purple box) and compensation capacitor (orange box) are shown.

The input to output power relation is linear and the efficiency of the full-bridge synchronous rectifier, which is measured with precise multimeters, is above 80 % over a

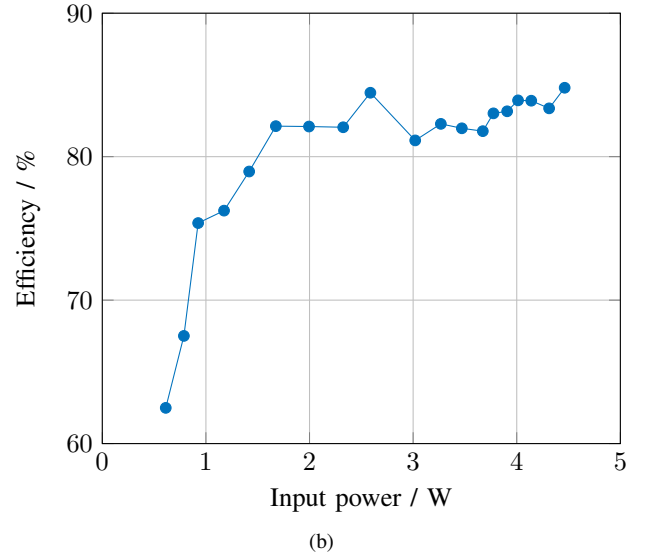
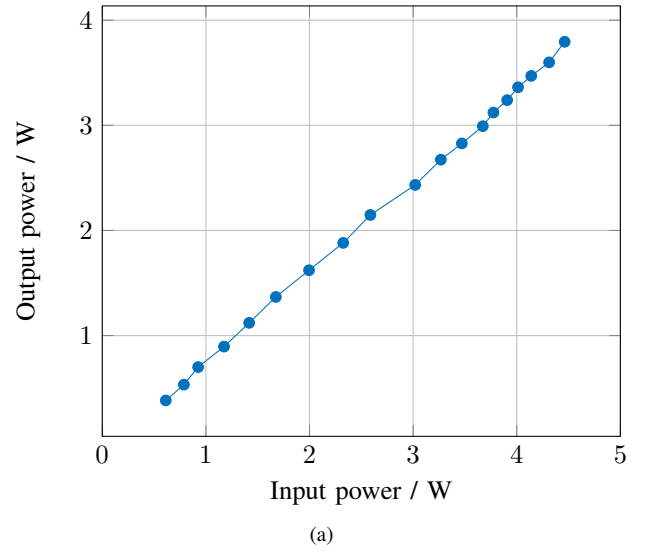


Fig. 11. The input output power relation (a) and efficiency of the prototype (b)

wide load range. Fig. 11 shows these results. The Rx coil and circuit is arbitrarily placed on top of the Tx coil to resemble a consumer use case in the best possible way.

Afterwards, the distance between the Tx and Rx coils is gradually increased by adding multiple 0.75 cm thick foam bricks as pictured in Fig. 12. Fig. 13 is visualizing the result of this experiment. Again, the placement after each distance change was arbitrary, which explains the roughness of the efficiency plot as a function of distance. The rectifier achieves a peak efficiency of 89 % at 3 cm distance between Tx and Rx coils.

V. CONCLUSION

A full-bridge Class-DE receiver circuit for wireless power transfer applications fulfilling the AirFuel standard was analyzed using component stress factors. Low voltage GaN transistors were compared using figures of merit to silicon

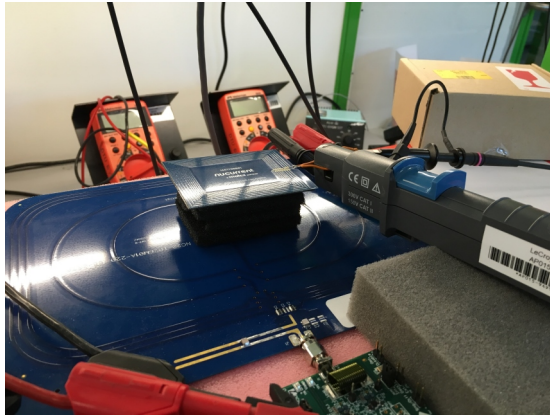


Fig. 12. Experimental setup for height measurement. There are multiple 0.75 cm foam bricks between the transmitter and receiver.

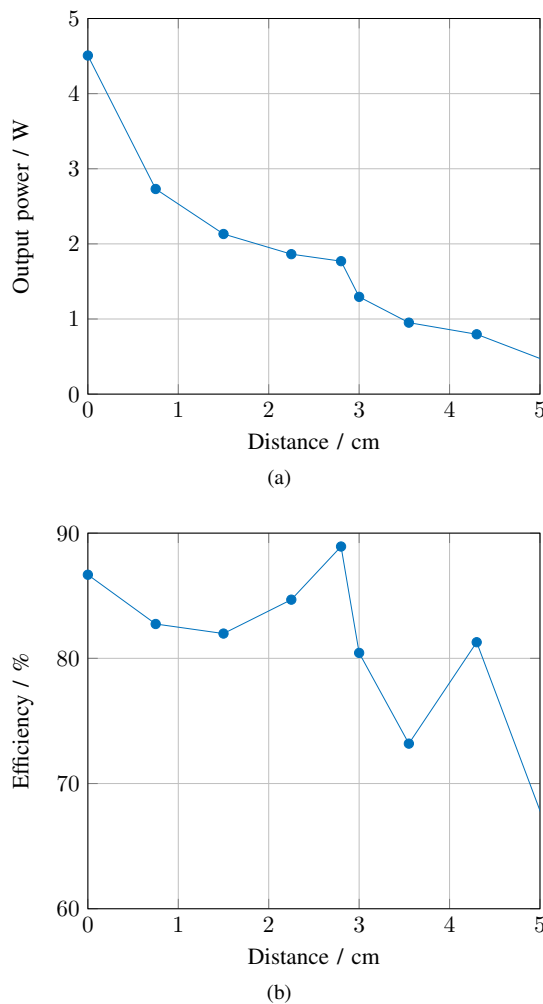


Fig. 13. Output power vs receiver distance from transmitter (a) and the efficiency of this (b)

transistors and used as synchronous rectifiers. The receiver was realized on a printed circuit board and matched to a 5 W receiver coil designed for the AirFuel operating standard. Together with an EPC transmitter base station, the receiver

was implemented in a wireless power transfer system. The efficiency of the rectifier circuit is well above 80 % over a wide load range. The system was able to transmit power above 1 W over a distance of 3 cm. Future work would look into optimization of the drive circuit and a way to have the drive circuit powered from either the input or output of the rectifier.

ACKNOWLEDGMENT

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